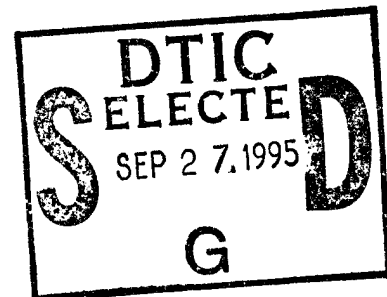California Institute of Technology

Robust Control of
Uncertain Nonlinear Systems

Final Report for ONR Young Investigator Award (N0001489J1678)

John C. Doyle
Caltech 116-81
Pasadena, CA 91125
(818) 395-4808
doylehot.caltech.edu

DTIC
SELECTED
SEP 2 7.1995
G

Accesion For		
NTIS CRA&I	☒	
DTIC TAB	☐	
Unannounced	☐	
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

19950925 034

94 8 22 1 26

DTIC QUALITY INSPECTED 1

Highlights

Substantial progress in a number of directions occurred during this program. Professor Doyle organized a 2-day workshop preceding the 1987 ACC on the subject of this program, with about 70 attendees. Several papers at the 1987 ACC reported on progress in nonlinear control (Doyle, Smith, and Enns, 1987 and Doyle and Packard, 1987), and robust control with an H_2 performance objective (Packard and Doyle, 1987). Progress has been made since on combining H_2 and H_∞ performance objectives, (Doyle, Zhou, and Bodenheimer (1989)).

New results on μ were reported at the 1988 ACC in Packard and Doyle, (1988) and Fan, Tits, and Doyle, (1988). Later, new methods for the computation of Structured Singular Values (SSV or μ) were developed based on Packard, Fan, and Doyle (1988), Fan, M., A. Tits, and J. Doyle (1990) and Young and Doyle (1990), with especially exciting results for the real-parameter case (Young, Newlin and Doyle (1991)). Work continued in extending the μ framework in directions that should lead to more effective methods for system identification (Newlin and Smith (1991)).

Progress has also continued on basic H_∞ theory. New state space formulas were obtained for H_∞ optimal controllers that dramatically simplify both the theory and computation (Doyle, Glover, Khargonekar, and Francis, 1988 and Glover and Doyle, 1988, and Doyle, Glover, Khargonekar, and Francis (1989)). A new characterization of H_∞ optimal controllers gives insight into their relationship with classical control methods (Lenz, Khargonekar, and Doyle, 1988).

Several new results were obtained extending standard analysis techniques to Linear Fractional Transformations (LFT) using Structured Singular Value, μ, and Linear Matrix Inequalities (LMI) in solving LFT problems. LFTs and LMIs play a very important role in postmodern control theory by providing a framework that unifies many concepts and generalizes transfer functions and their state-space realizations to include uncertainty. Doyle, Zhou, and Packard (1991) reviews known results on robust stability and performance and establishes a common and unified framework for the companion papers, which consider generalizations and extensions of balanced realizations and model reduction (Wang, Doyle, Beck, and Glover, 1991), stabilization (Lu, Zhou, and Doyle, 1991), optimal control (Packard, Zhou, Pandey, and Becker, 1991) , mixed real/complex μ (Young, Newlin and Doyle, 1991), model validation (Newlin and Smith, 1991), and LMI computation (Beck, 1991).

On the application front, a case study session was organized for the 1987 IFAC World Congress in Munich. Papers included a review of μ-based theory (Doyle, 1987) and its application to a process control problem (Smith, Doyle, Morari, and Skjellum, 1987). Additional applications were presented at the 1988 ACC (Balas and Doyle, 1988 and Smith and Doyle, 1988). All of these applications involved actual implementations using laboratory experiments. Applications papers on distillations columns (Skogestad, Morari, and Doyle (1989)) and flexible structure (Balas and Doyle (1989)) were also published.

Awards and publications

Awards

Two papers received major awards during this program. Doyle, Glover, Khargonekar, and Francis (1989) received the Axelby Prize from the IEEE Control System Society for the outstanding paper in the IEEE Transactions on Automatic Control and the IEEE W. R. G. Baker Outstanding Paper Award. The latter award is for the best paper reporting original research results in all of the IEEE publications, and it is the first time the award has been given to a paper in the controls area. Skogestad, Morari, and Doyle (1988) also won the Axelby Prize.

Publications

Journals

1. "When is a controller H_∞ optimal?" K. Lenz, P. Khargonekar, and J. Doyle, *Math. Control Signals and Systems*, 1988.
2. "State-space formulae for all stabilizing controllers that satisfy an H_∞-norm bound and relations to risk sensitivity," K. Glover and J. Doyle, *Systems and Control Letters*, vol. 11, 1988.
3. "Robust control of ill-conditioned plants: high-purity distillation," S. Skogestad, M. Morari, and J. Doyle, *IEEE T-AC*, December, 1988 (Outstanding Paper Award Winner).
4. "State-space solutions to standard H_2 and H_∞ optimal control problems," J. Doyle, K. Glover, P. Khargonekar, and B. Francis, *IEEE T-AC*, August, 1989 (Outstanding Paper Award Winner).
5. " Identification of Flexible Structures for Robust Control," G. Balas and J. Doyle, *IEEE Control Systems Magazine*, June, 1990.
6. "Beyond singular values and loopshapes," G. Stein and J. Doyle, *AIAA Journal of Guidance and Control*, December, 1990.
7. "Quadratic stability with real and complex perturbations," A. Packard A. and J. Doyle, *IEEE Trans. on Auto. Control*,1990, AC-35:198-201.
8. "Robustness in the presence of mixed parametric uncertainty and unmodeled dynamics," M.K.H. Fan, A. Tits, and J. Doyle, *IEEE T-AC*, January, 1991.
9. "Model Validation: A Connection between Robust Control and Identification," R. Smith and J. Doyle, *IEEE T-AC*, July, 1992.

Books

1. *Feedback Control Theory*, J. Doyle, B. Francis, and A. Tannenbaum, MacMillan, 1990.

Conference proceedings

1. "Robustness of uncertain nonlinear and time-varying systems," A. Packard and J. Doyle, 1987 ACC.

2. "Control of plants with input saturation nonlinearities," J. Doyle, R. Smith and D. Enns, 1987 ACC.

3. "A review of μ-based control design techniques," J. Doyle, 1987 IFAC Triennial World Congress.

4. "Feedback design for a large space structure experiment," G. Balas and J. Doyle, 1987 IFAC Triennial World Congress.

5. "A case study using μ: laboratory process control problem," R. Smith and J. Doyle, 1987 IFAC Triennial World Congress.

6. "On robustness under parametric and dynamic uncertainties," M.K.H. Fan, A. Tits, and J. Doyle, 1988 ACC.

7. "Structured singular values with repeated scalar blocks," A. Packard and J. Doyle, 1988 ACC.

8. "Controller order reduction with guaranteed system stability and performance," K. Lenz, P. Khargonekar, and J. Doyle, 1988 ACC.

9. "On the Caltech experimental large space structure," G. Balas and J. Doyle, 1988 ACC.

10. "Nonlinear controllers in an H_∞ framework: a design case study," R. Smith and J. Doyle, 1988 ACC.

11. "The two tank experiment: a benchmark control problem," R. Smith and J. Doyle, 1988 ACC.

12. "A power method for the structured singular value," A. Packard, M. Fan, and J. Doyle, 1988 CDC.

13. "Model validation: a connection between robust control and identification," R.S. Smith and J.C. Doyle, 1989 American Control Conference, Pittsburgh, PA.

14. "Optimal control with mixed H_2/H_∞ performance," J.C. Doyle, K. Zhou, and B. Bodenheimer, 1989 American Control Conference, Pittsburgh, PA.

15. "Vibration damping and robust control of the JPL/AFAL experiment using μ-synthesis," G.J. Balas, C.-C. Chu, and J. Doyle, 1989 IEEE Conference on Decision and Control, Tampa, FL.

16. "Mixed H_2/H_∞ control," K. Zhou, J. Doyle, K. Glover, and B. Bodenheimer, 1990 American Control Conference, San Diego, CA.

17. "Towards a methodology of robust parameter identification," R.S. Smith and J.C. Doyle, 1990 American Control Conference, San Diego, CA.

18. "Collocated versus noncollocated multivariable control of flexible structures," G.J. Balas and J.C. Doyle, 1990 American Control Conference, San Diego, CA.

19. "Computation of μ with real and complex uncertainties," P.M. Young and J.C. Doyle, 1990 IEEE Conference on Decision and Control, Honolulu, HI.

20. "Robustness and performance tradeoffs in control design for flexible structures," G.J. Balas and J.C. Doyle, 1990 IEEE Conference on Decision and Control, Honolulu, HI.

21. "Computation of μ with real and complex uncertainties," P.M. Young and J.C. Doyle, 1991 IEEE Conference on Decision and Control, Brighton, UK.
22. "LFTs, LMIs and μ," J. Doyle, A. Packard, and K. Zhou, 1991 IEEE Conference on Decision and Control, Brighton, UK.
23. "Stability and stabilization of LTI multidimensional systems," W. Lu, K. Zhou, and J. Doyle, 1991 IEEE Conference on Decision and Control, Brighton, UK.
24. "Stability and model reduction of linear fractional transformations," W. Wang, J.C. Doyle, C. Beck and K. Glover, 1991 IEEE Conference on Decision and Control, Brighton, UK.
25. "Structured Singular Value Analysis with real and complex uncertainties," P. Young, M. Newlin, and J. Doyle, 1991 IEEE Conference on Decision and Control, Brighton, UK.